Effect of TiN Coating on SNS AR Kicker Performance

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1. Introduction.

The presence of a surface with a large enough secondary emission coefficient (SEC) inside the vacuum chamber of SNS accumulator ring can cause resonant multiplication of electron charge trapped inside the proton beam, and lead to the so called ‘e-p’ instability. Therefore a thin layer of TiN having small secondary electron coefficient will be deposited on the inner surface of the vacuum chamber. Besides the vacuum chamber itself there are different inserts exposed to the beam electric field such as pickups, wall current monitors, kickers, cavities etc. In general each of these objects should have a low SEC on the surface facing the beam. Extraction kickers have large surfaces of ferrite directly exposed to the beam and ferrite is known to have a large SEC. Its surface must be treated somehow in order to provide acceptable SEC. It would be attractive to use the same TiN coating, as on the rest of the vacuum chamber, but TiN film is a good conductor and it can affect kicker performance due to eddy currents in the coating layer. The rise/fall time of the magnetic field in the presence of a TiN layer and the resulting heating due to eddy currents are estimated below.

2. Rise-time of magnetic field due to eddy current effect.

If magnetic flux through a conducting surface changes, eddy currents are induced in a manner to keep the flux constant. The new flux level is established only after attenuation of the induced currents due to the final conductivity. Transient process can be described as field diffusion with a time constant given by following expression [1]:

$$\tau \cong \frac{\mu_0}{\pi^2}\frac{1}{R_S}\frac{a^2 b^2}{g(a^2+b^2)},$$

where R_S is surface resistance, a is the kicker height, b is the kicker length, and g is the gap width. It is assumed that the conducting layer is much thinner than the gap. Substituting $\mu_0 = 4\pi\cdot 10^{-7}$ we obtain the following practical expression:

$$\tau[ns] \cong 127\cdot\frac{1}{R_S}\frac{a^2}{g(\frac{a^2}{b^2}+1)} \approx 1.27\frac{a^2[cm^2]}{R_S[\Omega/sq]\; g[cm]}$$

For the SNS kicker a =14cm, g =11cm and $\tau << 200ns$ have to hold in order not to affect normal kicker performance. This gives a limitation on the acceptable surface resistance:

$$R_S >> 1.27\frac{14^2}{11\cdot 200} \cong .11\Omega / sq.$$

Surface resistance $R_S = \dfrac{\rho}{d}$, where ρ is coating resistance, and d is the coating thickness. Therefore the thickness of the coating has to satisfy: $d << \dfrac{\rho}{0.11}$. Resistance of TiN is $\rho = 25\mu\Omega\cdot cm$ [2], which gives a limit for the layer thickness of $d << 2.3\mu m$. A practical value of coating thickness providing low SEC and reasonable lifetime of about 0.1 μm [3] satisfies the above condition with good margin.

2. Power dissipation in the coating layer.

Eddy currents can dissipate considerable power in the conducting layer. Instant power per unit area can be estimated as:

$$P_S = \frac{E^2}{R\cdot\delta S} = \frac{\dot{\Phi}^2}{R\cdot\delta S} = \frac{\dot{B}^2\cdot a^2\cdot b^2}{\rho\cdot\dfrac{2(a+b)}{d\cdot\delta}}\frac{1}{2(a+b)\delta} = \frac{\dot{B}^2}{4\rho}\frac{a^2\cdot d}{\left(1+\dfrac{a}{b}\right)^2} \approx \frac{B_{\max}^2}{4\rho\tau^2}\frac{a^2\cdot d}{\left(1+\dfrac{a}{b}\right)^2},$$

where ρ is the coating material resistivity, a is the kicker height, b is the kicker length, d is the layer thickness, $B_{\max}$ is the maximum kicker field, and τ is the field risetime. Energy deposition per unit area is:

$$Q_S = P_S\cdot\tau = \frac{B_{\max}^2}{4\rho\tau}\frac{a^2\cdot d}{\left(1+\dfrac{a}{b}\right)^2}.$$

It gives a temperature rise of

$$\Delta T = \frac{Q_S}{C} = \frac{Q_S}{c_m\cdot\lambda\cdot d} = \frac{B_{\max}^2}{4\rho\tau\lambda c_m}\frac{a^2}{\left(1+\dfrac{a}{b}\right)^2},$$

where λ and c_m are the specific heat of unit mass and the density of coating material respectively. Substituting $B_{\max} = .02T$, $\tau = 200ns$, $\lambda = 5200\dfrac{kg}{m^3}$, $\rho = .25\mu\Omega\cdot m$, $c_m = 500\dfrac{J}{kg}$ we obtain:

$$\Delta T[^\circ] \approx 7.69\cdot 10^{-2}\frac{a[cm]^2}{\left(1+\dfrac{a}{b}\right)^2}.$$

For $a = 14cm$, $b = 40cm$ we have $\Delta T \approx 8.27^0 C$ after each pulse. Note that ΔT doesn't depend on d therefore it cannot be reduced by reducing the coating thickness. But reducing a reduces dissipated energy considerably. If we divide the conducting layer by narrow nonconducting gaps on N strips along side *b*, similar to lamination in laminated magnets, the temperature rise becomes:

$$\Delta T[^\circ] \approx 7.69 \cdot 10^{-2} \frac{a[cm]^2}{\left(1 + \frac{a}{bN}\right)^2} \frac{1}{N^2}.$$

For $N = 3$ we have $\Delta T = .92^0 C$ which is negligible. The average dissipated power per unit area in this case is:

$$P_{av} = 2 \cdot Q_S \cdot f = \frac{B_{\max}^2}{2\boldsymbol{rt}} \frac{a^2 \cdot d \cdot f}{\left(N + \frac{a}{b}\right)^2} \approx \frac{B_{\max}^2}{2\boldsymbol{rt}} \frac{a^2 \cdot d \cdot f}{N^2},$$

where f is the repetition rate and the pulse trailing edge is taken into account by doubling the energy. For the above parameters and $f = 60Hz$ the average power dissipation is

$$P_{av}[\frac{W}{cm^2}] \approx .47 \cdot d[\boldsymbol{m}m].$$

For a coating thickness of 0.1 μm, we have $P_{av} = .047 \frac{W}{cm^2}$ which is negligible. Note that laminating of the conducting layer reduces the field diffusion time constant as well by almost $\frac{1}{N^2}$. Therefore the kicker performance becomes almost insensitive to the coating thickness.

3. Conclusion.

The analysis above shows that the extraction kicker performance with a thin TiN coating applied to the ferrite surface is limited by surface heating from eddy currents. However, if the conducting layer is divided into separate pieces of smaller size, heating is reduced drastically as well as the field diffusion time. The maximum size of the pieces of about 1-2 cm looks reasonable from both physical and technical points of view, and should be determined by more detailed analysis.

References.

1. P.I. Bryant. Basic Theory for magnetic measurements, CERN School

2. http://www.brycoat.com/physprop.html